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Land use impacts on biodiversity in LCA: proposal of characterization factors based on functional diversity

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Abstract
Purpose The focus of land use modeling in life cycle impact assessment has been mainly on taxonomic measures of biodiversity, namely species richness (SR). However, increasing availability of trait data for species has led to the use of functional diversity (FD) as a promising metric to reflect the distinctiveness of species; this paper proposes the use of an FD index to calculate characterization factors (CFs) for land use impacts. Furthermore, we compare the results of the CFs to current practice and assess the increase in complexity introduced by the use of the new indicator.
Methods The model proposed is based on data compiled by previous regional meta-analysis on SR and FD, in different land use types in the Americas. The taxonomic groups included were mammals, birds, and plants. Within each study, calculated values for FD for different land use types were compared with the natural or close-to-natural state, taken as the reference situation. FD values among different land uses were standardized, and CFs were calculated. The final results were then analyzed and compared by analysis of variance and post hoc tests. A sensitivity analysis was also applied to verify the influence on the choice of the reference state.
Results and discussion The results show that significant differences exist between CFs for SR and FD metrics. Across all taxa, CFs differ significantly between land use types. The results support the use of CF for FD, as a complement to current practice. Distinct CFs should be applied for at least six groups of land use categories. The choice of reference land use type did not significantly alter the results but can be a source of variability. A sensitivity analysis evaluating the impact of alternate land use types as reference types found only few significant changes on the results.

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Conclusions and recommendations Given the results, we believe the use of CFs based on FD can help on the establishment of possible links between species loss and key ecosystem functions, i.e., on the association between the midpoint indicator (e.g., biodiversity loss) and the damage caused to ecosystem quality, in terms of functions lost. Basing CFs on FD is not without challenges. Such indices are data hungry (requiring species composition and traits) require more complex calculations than current common practice, including decisions on the choice of a method to calculate FD and the selection of traits.

Keywords Biodiversity indicator · Functional diversity · Global characterization factors · Land use · LCIA · Regionalization

1 Introduction

The Millennium Ecosystem Assessment (MA 2005) assessed the consequences of global ecosystem changes, finding that land use change is one of the main direct drivers of biodiversity loss, thus impacting the provision of ecosystem services and human well-being. According to the Millennium Ecosystem Assessment, the conversion rate of natural areas on Earth has increased dramatically in the last 50 years especially in tropical and subtropical regions, with many biomes have undergone up to 50 % change. A direct consequence of such actions is the loss of biological diversity, observed by measures such as the reduction in population size, increase in homogeneity of species composition and increases in species extinctions (MA 2005).

In life cycle impact assessment (LCIA), the focus of modeling land use impacts on biodiversity indicators has been mainly on taxonomic measures (Curran et al. 2011; Vandewalle et al. 2010), such as species richness (SR) (Achten et al. 2008; Koellner 2003; Mueller-Wenk 1998; Schmidt 2008; Weidema and Lindeijer 2001). However, the use of SR alone masks the functional role that species play in their habitat (Mouchet et al. 2010). Species are assigned an equal weight, regardless of their functional characteristics and contributions despite the recognition that species loss implies potential changes in the ecosystem related functions. For example, carbon storage, nutrient cycling and biotic productivity are influenced and affected by activities of species. More recently, several researchers have emphasized functional diversity (FD) as a more appropriate indicator of biodiversity loss in comparison to taxonomic indicators because of the association between species traits and ecosystem functions (Díaz and Cabido 2001; Flynn et al. 2009; Mouchet et al. 2010; Petchey and Gaston 2006).

FD is a reflection of the range and value of the quantifiable aspects of species—such as feeding behavior, quantity of resources consumed, phosphorus uptake, etc.—which are measurable at the level of the individual (Petchey et al. 2009), which if chosen appropriately can act as indicators of the roles species play and the rules by which they assemble into communities (Vandewalle et al. 2010) and how they influence the way ecosystems operate (Tilman 2001). The basis for calculation of FD is a set of functional traits, namely the morphological physiological, or behavioral characteristics of organisms (e.g., seed size, leaf area, wood density, or plant size, for plants) which can reveal their response to environmental pressures (response traits) or the effects they have on ecosystem processes (effect traits) (Harrington et al. 2010). According to Hooper et al. (2002), ecosystem processes are more greatly affected by functional differences among species in an ecological community than their taxonomic richness or composition. Theoretically, change in SR does not ensure a change in ecosystem processes. The loss of species can be compensated by other species playing similar functional roles in an ecological community. Trait-based measures of FD permit a preliminary assessment of redundancy or complementarity between species and the functions they play. These relationships cannot be captured by species counting—as currently done in LCIA. Any change in species composition has consequences on the quantity, range and combination of functional traits and therefore has a direct influence on the regulation of processes in an ecosystem (Chapin III et al. 2000).

There are two ways to quantify FD: (1) *discontinuous measures*, i.e., group/guild-based, such as the classification of species traits according to functional group richness and (2) *continuous measures*, in which species are not divided among functional groups (Petchey and Gaston 2006; Petchey et al. 2009). Continuous measures all start with calculations of the multivariate distance between each pair of species in an assemblage. Group-based measures may not be appropriate for all ecosystem processes and a large amount of decisions and assumptions are required, such as where to place the boundaries of each group and the number of groups to include. Most importantly, substantial functional differences among species are likely to be disregarded in some cases when forming these functional groups. The second approach consists in calculating the distances between species based on their trait values, and then summarizing these distances by hierarchical clustering into a dendrogram (Petchey and Gaston 2006). Univariate measures based on the abundance-weighted range of each trait have also been developed (Mason et al. 2003, 2005) after estimating the within study and between study variance.

The calculation of FD index represents a further step on the assessment of land use impacts and potentially complement current practice in LCIA focusing on SR. In order to increase the environmental relevance of the land-use biodiversity impact

indicator by better accounting for each species' role in an ecosystem and its stability, the objectives of this study are:

1. Use a FD index covering several taxonomic levels for the calculation of characterization factors for land use impacts on biodiversity in LCIA.
2. Evaluate its influence on biodiversity characterization factors compared with current practice.
3. Assess how far increased complexity and data requirements of the new biodiversity indicator are justified by improved completeness, reliability, and environmental relevance.

2 Methods

The model proposed is based on data compiled by Flynn et al. (2009) who analyzed data on SR and FD across land use intensification gradients, and studies compiled by Gibson et al. (2011). We include three taxonomic groups in this study: (1) mammals, (2) birds and (3) plants, mainly due to trait data availability. The FD index for each study area was completed according to Petchey and Gaston (2002b) using presence–absence information for each species.

Figure 1 shows a schematic view of the data needed for the calculation of characterization factors for land use impact assessment based on SR and FD. For methodological comparison, we assess differences between the characterization factors based on FD and SR for different taxonomic groups and across land use types.

Under the framework for LCIA of land use, two types of land interventions can be distinguished, land use (occupation) and land use change (transformation). However, we only calculate characterization factors for occupation impacts in this model because most of the studies used in the analysis did not have information on the previous land use state, which is essential for calculating characterization factors for transformation models. Nor was information on ecosystem recovery collected for this study.

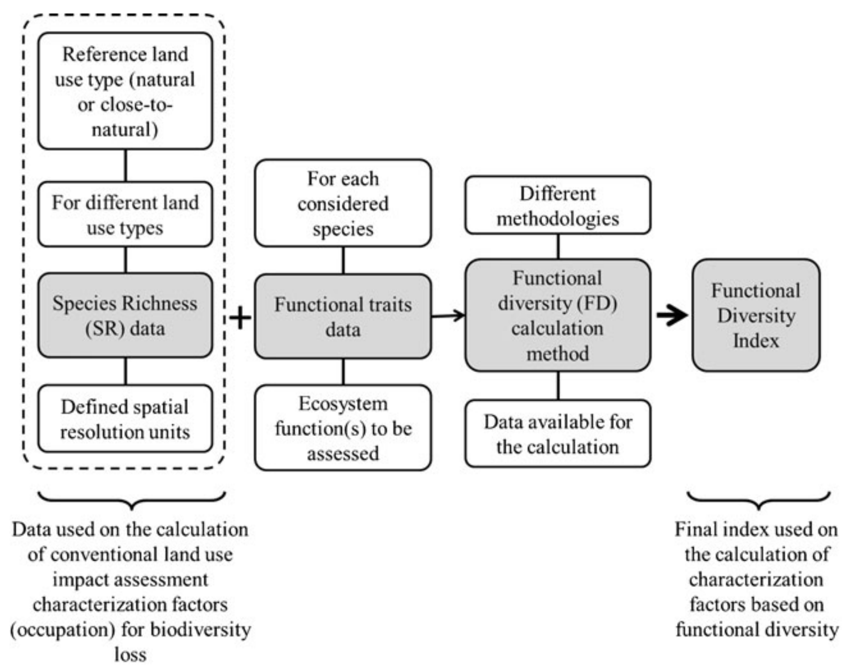
Here, we consider that species not found in a certain land use type, in relation to the reference land use, represents species loss. The same is true for FD. We emphasize the species can be lost without exhibiting changes in FD when one or more species playing the same functional role as the lost species is retained.

2.1 Data sources

The main data sources used in this paper were collected by Flynn et al. (2009), in order to carry out an analysis on the impact of land use intensity change on SR and FD. In that paper, the authors have used three land use categories, ranging from natural (e.g., primary forest) to semi-natural (e.g., grazed pasture lands) to agricultural (e.g., row crops) systems. However, due to the more complex land use classification used in LCA, it was essential to investigate the differences among more specific land use subcategories. Therefore, additional studies were added to the original Flynn et al. (2009) study to allow the completeness of the analysis carried out in this paper. The added studies were cited in Gibson et al. (2011) who assessed the impacts on biodiversity in the tropics using a meta-analysis of 138 studies.

Data on functional traits for the additional studies were collected from national species databases, such as the Costa

Fig. 1 Data and methodological scheme applied on the calculation of characterization factors for land use based on SR and FD



Rica's *National Biodiversity Institute* (*INBio*), the *Portal Brasil 500 Passaros*, the *Animal Diversity Web*, and the online guide *Birds of Surinam*. Global databases such as *BirdLife International*, *Global Species*, *NeotropicalBirds*, and *Avian Web* have been used when data were not found in national databases.

The mammal meta-analysis included 12 studies conducted in Bolivia, Brazil, Peru, Panama, Costa Rica, Mexico, the USA, and Canada (Table S1 in the Electronic supplementary material (ESM). Plant data (Table S2 in the ESM) ranged from Costa Rica to eastern Canada. Bird data (Table S3 in the ESM) were gathered in Brazil, Costa Rica, Mexico, and the USA. Figure 2 presents the spatial location of the data among different ecoregions.

Tables S1, S2, and S3 (ESM) contain more detailed information on the data used in the calculations. Data on FD, SR, characterization factors for FD and SR, land use types and ecoregion are available for each of the studies, for all three taxonomic groups.

2.2 Land use types

The different land use types present in the studies have been aligned with the land use types classification of the UNEP/SETAC LULCIA proposal, following Koellner et al. (2013). The reference situation chosen to represent the potential natural vegetation (PNV) was the most natural or close-to-natural state present in each of the studies included in the meta-analysis, i.e., primary forest. It is important to emphasize that no information on SR of previous natural land cover was available in any of the studies and the actual land cover was then used. By natural or close-to-natural state, we mean land cover types which require a long time for restoration (Koellner and Scholz 2007) after disturbance, i.e., land use types that represent a stable climax community representative of the PNV of the study region given the current climatic and edaphic conditions and that show minimal signs of current or recent (i.e., past decades) anthropogenic disturbance. For PNV, we use the concept used by Zerbe (1998) and Chiarucci et al. (2010) and introduced by Tüxen (1956) defined as the hypothetical natural state mature vegetation would reach, in a split of second, if all anthropogenic interventions would be removed at once. The studies on mammals, plants and birds included 13, 13, and 15 different land use types, respectively (Table 1). For details, see the supplementary Tables S1, S2, and S3 in the ESM.

2.3 Functional trait data

The functional traits applied on our analysis were the same used in Flynn et al. (2009), because they are the most available traits relating species loss with key ecosystem functions (Petchey and Gaston 2002a). Accordingly, the main traits chosen for this analysis were: (1) resource use and behavioral traits for mammals and birds and (2) morphological and anatomical traits for plants, related to the species capacity to capture resources (Table 2). The same traits information was also compiled for the studies cited in Gibson et al. (2011).

We stress that the objective of this paper is not specifically to analyze the link between changes in FD and changes in ecosystem functions. We recognize that the link between species loss and different ecosystem functions needs to be

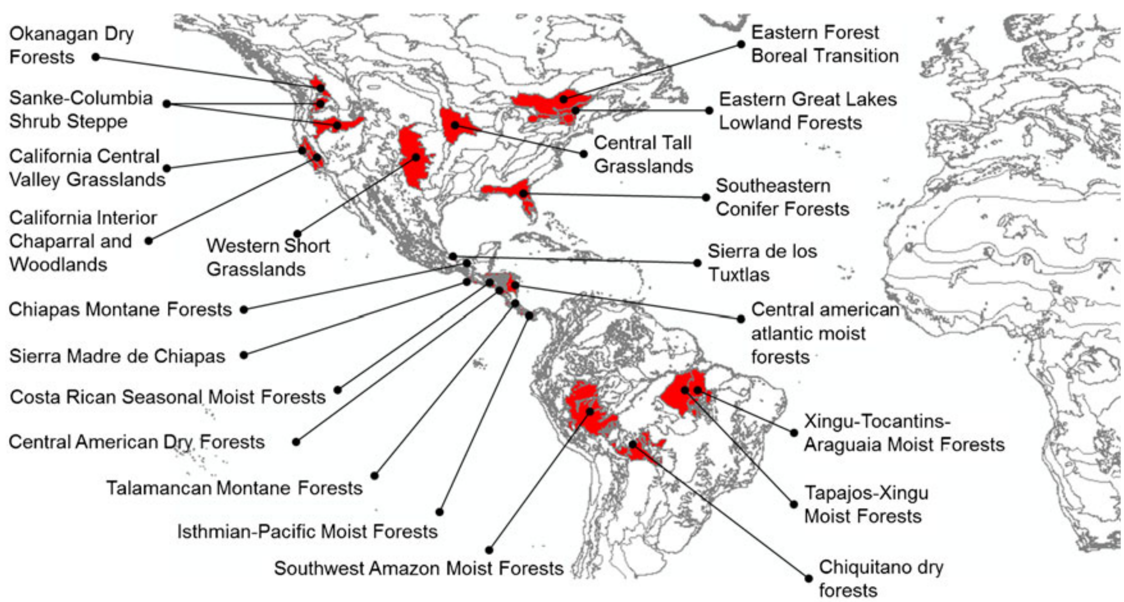


Fig. 2 Ecoregions for which data on SR have been sampled. The map shows North America and the Central-Northern part of Latin America

Table 1 Land use and cover classification used in LCA and respective codes (Koellner et al. 2013)

Code	Land-use-type classification
[1]	Forest
[1.1.1]	Forest, primary
[1.1.2]	Forest, secondary
[1.2.1]	Forest, extensive
[2.2]	Wetlands, inland
[3]	Shrubland
[4]	Grassland
[4.2]	Pasture/meadow
[5.1.1]	Agriculture, arable, fallow
[5.1.2]	Agriculture, arable, non-irrigated
[5.1.2.1]	Agriculture, arable, non-irrigated, extensive
[5.1.2.2]	Agriculture, arable, non-irrigated, intensive
[5.1.6]	Field margins/Hedgerow
[5.2.1]	Agriculture, permanent crop, non-irrigated
[6]	Agriculture, mosaic
[7.6.3]	Traffic area, railroad, embankment
[10.1.2]	Rivers, artificial
[10.2.2]	Lakes, artificial

further investigated, but this is beyond the scope of the current study.

2.4 FD calculation

We used Petchey and Gaston's index of FD in this study (Petchey and Gaston 2002b; Petchey et al. 2004, 2009) such as in Flynn et al. (2009). Four steps are involved in the calculation of Petchey and Gaston's FD index: (1) construction of a matrix containing species' traits values (Fig. 3a); (2) calculation of the multivariate distances between species, using these trait values (see Fig. 3b); (3) hierarchical clustering of the distance matrix into a dendrogram, which is a tree diagram, used to depict the arrangement of clusters (see Fig. 3c); (4) calculation of FD values based on the total branch length of the dendrogram, for the species present in a particular community. Although abundance-weighted measures of FD exist, we relied solely on presence-absence data in this study due to the lack of species abundance data in some of the studies.

The distance matrix is used to estimate the similarity among organisms, in terms of the differences in the trait values. We used Gower's distance metric to calculate the distance between species based on their traits, as this distance metric allows the use of multiple data types, including categorical and binary data (Podani and Schmera 2006).

After obtaining FD values, we normalized values to a value of 1 for the reference land use type, in each study as in Eqs. (1) and (2) to evaluate FD and SR differences within studies.

$$FD_N = FD_i/FD_{ref} \tag{1}$$

$$SR_N = SR_i/SR_{ref} \tag{2}$$

where FD_N and SR_N are the normalized values for FD and SR, respectively. FD_i corresponds to the calculated FD value for a certain land use type *I*, and FD_{ref} is the FD value for the

Table 2 Functional traits and respective categories used for functional diversity calculation (Flynn et al. 2009)

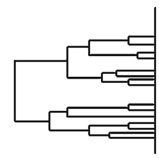
Taxonomic group	Trait	Categories
Birds	Mass	–
	Feeding guild	Carnivore, herbivore, insectivore, and omnivore
	Food type	Invertebrates, small fruits, seeds, nectar, fish, and generalist
	Foraging location	Ground, upper canopy, shrub layer, mid-canopy, forage throughout, and aquatic
	Foraging habitat	Ground, leaves, perch and attack, stems, aerial, water, hover, soar and attack, and other
Mammals	Mass	–
	Feeding guild	Carnivore, herbivore, insectivore, and omnivore
	Food type	Invertebrates, fruit, seeds, vertebrates, and vegetation
	Activity	Diurnal, nocturnal, and either
	Nesting	Aquatic, arboreal, burrows, multiple, and terrestrial
Plants	Leaf area	–
	Height	–
	Fruit type	Fleshy and not fleshy
	Fruit length	–
	Foliage	Deciduous and evergreen
	Growth form	Tree, shrub, tall herb, low herb, and grass
	Leguminous	Legume and not legume

$$T = \begin{pmatrix} v_{1,1} & v_{1,2} & \cdots & v_{1,t} \\ v_{2,1} & v_{2,2} & \cdots & v_{2,t} \\ \cdots & \cdots & \cdots & \cdots \\ v_{s,1} & v_{s,2} & \cdots & v_{s,t} \end{pmatrix}$$

(a)

$$D = \begin{pmatrix} 0 & d_{1,2} & \cdots & d_{1,s} \\ d_{2,1} & 0 & \cdots & d_{2,s} \\ \cdots & \cdots & \cdots & \cdots \\ d_{s',1} & d_{s',2} & \cdots & 0 \end{pmatrix}$$

(b)



(c)

Fig. 3 Elements involved on the calculation of Petchey and Gaston's FD Index: **a** trait matrix, with trait values *v* corresponding to species *s*, and trait *t*; **b** distance matrix, with the pair-wise distances between species; and **c** dendrogram, from which the FD values are calculated

reference land use type. SR_i and SR_{ref} are the corresponding values for SR.

Contrary to data transformations used by Flynn et al. (2009) to compare across studies within land use types, we preferred normalization to the computation of standardization. In such a way, reference land use types receive a value equal to 1, which is more suitable for the calculation of occupation impact values.

We use the natural or most close-to-natural land use type as the chosen reference for the normalization procedure (Tables S1 (for mammals), S2 (for plants), and S3 (for birds) in the ESM). However, when more than one natural or close-to-natural land use types were available within one study, we used a sensitivity analysis to verify if a change in the results would be observed, by changing the reference land use type.

2.5 Calculation of characterization factors

We calculated characterization factors based on the natural logarithm transformation of normalized FD and SR values to adjust the variables to a normal distribution since differences within and among studies exist (i.e., area size, sampling techniques, etc.). The formulas used for FD and SR are shown in Eqs. (3) and (4), respectively.

$$\mathrm{CF_{FD}} = -ln(\mathrm{FD}_N) \tag{3}$$

$$\mathrm{CF_{SR}} = -ln(\mathrm{SR}_N) \tag{4}$$

for which FD_N and SR_N are the normalized values for FD and SR, respectively (Tables S1 (for mammals), Table S2 (for plants), and S3 (for birds) in the ESM). The minus sign on Eqs. (3) and (4) was inserted in order to be consistent with characterization factors calculated in other models (and LCIA impact categories), where impact is expressed in positive values.

An illustration on how the characterization factor would be applied in LCIA, to calculate the occupation impact (OI) is represented in Eqs. (5) and (6), following Eqs. (3) and (4), respectively.

$$\mathrm{OI_{FD}} = \mathrm{CF_{FD}} \times A_{\mathrm{occ}} \times t_{\mathrm{occ}} \tag{5}$$

$$\mathrm{OI_{SR}} = \mathrm{CF_{SR}} \times A_{\mathrm{occ}} \times t_{\mathrm{occ}} \tag{6}$$

A_{occ} represents the area of occupation and t_{occ} the time of occupation.

FD is a complement of SR, i.e., the FD index indicates how FD changes (decline or increase) and at which rate, when land use change takes place. This can indicate low or high redundancy in communities. However, they should not be aggregated into one index, once FD index already takes into account SR data, but they are rather alternatives to represent impacts of land use and land use change on biodiversity.

2.6 Statistical analysis

Differences between the characterization factors ($CF_{FD} \times CF_{SR}$) were assessed (1) for each taxonomic group and (2) among the different land use types existing in the studies. For comparison (1), pairwise *t* tests and nonparametric Wilcoxon's matched pairs test were applied (Table S4 in the ESM); the latter to assess whether deviation from normality affected the results. Comparison (2) implied an analysis of variance for all taxonomic groups using a significance value of 5 % (0.05). A post hoc test was applied to check which groups of data were particularly different from each other. We chose Fisher's least significant difference (LSD) test for post hoc comparisons among groups and used Mann–Whitney *U* tests to verify the results. We used Statistica 9.0 (StatSoft Inc 2009) to perform the statistical analyses. The nonparametric Mann–Whitney *U* test was also applied to verify the results (Table S5 in the ESM). Furthermore, we used a weighted analysis, using the SR and FD variance as a weight on the previously performed analyses (i.e., Mann–Whitney *U* and LSD tests), to test for the influence of differences in sample size and sample variability among the land use types. The within-study variance and the pooled variance, between studies, was calculated and the within and between study variation was compared. The weighting procedure was conducted, in order to correct large differences between studies variance. For the weighted-

variance analyses, the variance of FD and SR values was calculated for each of the studies. All the statistical tests were then re-run having these values as weight for each data point.

3 Results

3.1 Characterization factors for land use impacts on biodiversity

The references used and the calculated values of characterization factors for different land use types can be seen in Tables S1, S2, and S3 (ESM). These tables present the raw values for SR and calculated FD, the respective normalized values (SR_N and FD_N) and the calculated characterization factors based on SR data (CF_{SR}) and FD (CF_{FD}).

3.2 Differences between characterization factors CF_{FD} and CF_{SR} for each taxonomic group

Assessing differences between CF_{SR} and CF_{FD} for all three taxonomic groups (without considering different land use types) the paired *t* test revealed a significant difference for birds but not for mammals and plants (Table S4 in the ESM).

Similar results were obtained for Wilcoxon's matched pairs test. When this test was applied, taking into account different land use types, significant differences were found between CF_{FD} and CF_{SR} for "field margins/hedgerows" for "birds" and for "agriculture, mosaic" for "mammals." When the data of all groups was used on the analysis, significant differences were found for "agriculture, mosaic." Therefore, for these land use types, the results showed that the application of different indicators (SR or FD) could lead to different conclusions.

3.3 Difference between characterization factors for different land use types

The analysis of variance showed a degree of significance among the CF_{FD} and CF_{SR} values for different land use types. A significant difference among the population means was found for both CF_{FD} and CF_{SR}, at p levels of 0.0057 and 0.0003, respectively (Table S6 in the ESM).

Significant differences were also found among the CFs for different land use types, in the results of the post hoc Fisher LSD test and the nonparametric Mann–Whitney *U* tests (Table S5 in the ESM). The results show some distinct groups, mainly: (1) natural and close-to-natural forest land use types, such as "forest, primary," "forest, secondary," "forest, extensive," and "forest, intensive" as terrestrial; (2) "lakes, artificial" and "rivers, artificial" as water bodies; (3) "shrubland" and "field margins/hedgerows"; and (4) agriculture land use types, such as, "agriculture, arable, nonirrigated, intensive," "agriculture, mosaic," "agriculture, permanent crop, non-irrigated, intensive," "pasture/meadow," and "grassland." Other land use types such as "agriculture, arable, non-irrigated," "agriculture, arable, non-irrigated, extensive," and "agriculture, arable, fallow" did not present significant differences towards other land use types. No significant differences were observed within land use categories, such as forest and agriculture (e.g., between CFs for "forest primary" and "forest secondary").

The results show that managed landscapes presented a detrimental impact in terms of SR and FD loss (Fig. 4). Land use types with positive characterization factors (bigger impact, in relation to the reference land use types) for both SR and FD were: "agriculture, arable, fallow," "agriculture, arable, non-irrigated, intensive," "agriculture, mosaic," "agriculture, permanent crop, non-irrigated," "grassland," "pasture/meadow" and "wetlands, inland." Land use types with negative characterization factors (reduction in SR and FD impact, in relation to the reference) were "forest, primary," "forest, extensive," and "rivers, artificial."

The land use type "forest" had unexpected positive CF values. "Forest, primary" was taken as reference situation in 13 studies, "forest, secondary" and "forest" in five, each, and other land use types ("shrubland," "field margins/hedgerows," "grassland," and "forest, extensive") in the remaining five ones. CFs for "forest, secondary" mainly represents impact, when "forest, primary" is taken as reference land use type (see Daily et al. (2001) study on Table S3 in the ESM). For "forest, extensive", for which "forest, secondary" was mainly taken as reference, both CF_{SR} and CF_{FD} results in values below zero (richer in SR and FD). For "forest, intensive," CF_{SR} values were below zero and CF_{FD} mainly above zero.

For "agriculture, arable, non-irrigated" and "agriculture, arable, non-irrigated, extensive," CF_{FD} values represented impact, following the results for other agricultural land use types, while CF_{SR} values were mainly below zero.

CFs for "Traffic area, railroad, embankment" presents impacts (positive CFs) for SR and only one negative value for CF_{FD}, when "forest, primary" was taken as a reference land use type. In that study (Mayfield et al. (2006), the same is observed for "pasture/meadow" CF_{FD} and CF_{SR} values: they display positive impact, in comparison with "forest, primary."

"Forest" is taken as reference situation in five studies (i.e., CF=0 and therefore, no impact): (1) one bird study (Best et al. 1995), (2) two mammal studies (Husband et al. 2009; Suzan et al. 2008), and (3) two plant studies (Sanchez-Merlos et al. 2005a, b). In other four studies, it presents positive CFs when compared with the reference situations "forest, primary," "forest, extensive," and "shrubland." In order to verify the influence of these choices and the consequent differences between CF_{FD} and CF_{SR} for each

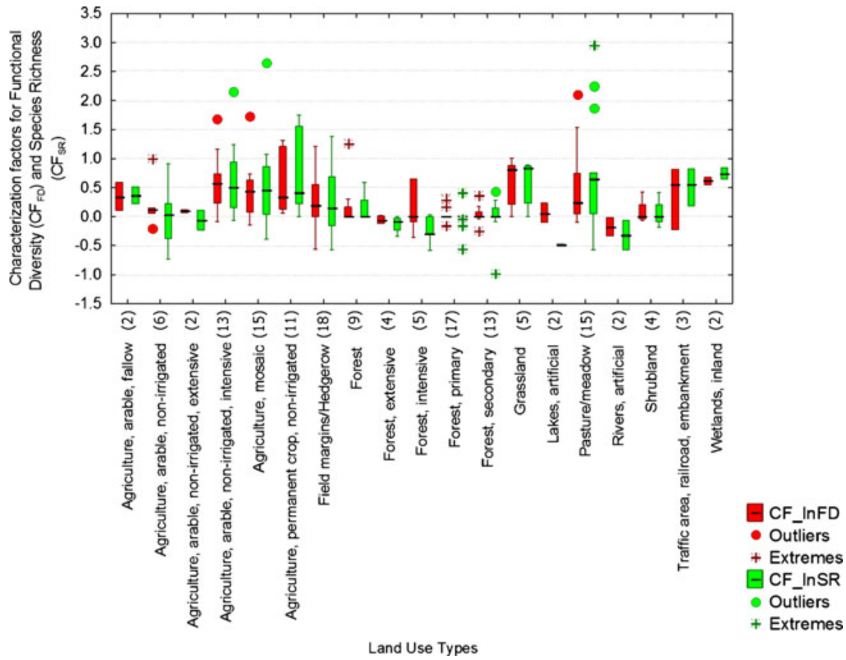


Fig. 4 Box–whisker plot of CF_{SR} and CF_{FD} grouped by land use types for all taxonomic groups (mammals, birds, and plants)

of the taxonomic groups and for all the data, an analysis of sensitivity was carried out.

3.4 Sensitivity analysis for the choice of reference land use types

Table 3 shows the new reference land use types, in comparison to the previous ones, used in the sensitivity analysis. For each taxonomic group, few significant changes in the results were observed when a different land use type was used as reference. The results for the t-tests are displayed in Table S8 in the ESM. It can be seen that significant differences between the means of the characterization factors for FD and SR have been found only for "plants." The results mainly varied due to the increase in values of FD and SR for the new reference type used for the Mayfield et al. (2006) study, in relation to the previous reference used, i.e., most values had a shift from negative to positive. For birds, the new reference values presented lower SR and FD values for both studies, especially in Mas et al. (2004) study, in which most values shifted from positive to negative. For different land use types the LSD test revealed differences between the CF_{FD} and CF_{SR} before and after the sensitivity analysis (Tables S5 and S7 in the ESM). The results of the weighted analysis showed quite different results, pointing out bigger differences among different land use types. For example, differences between crops, pastures, and traffic areas could be noted. It seems to be that unweighted it is more conservative estimate, because less significant results appear.

4 Discussion

Differences in the magnitude of change in SR and FD between broad land use categories, such as forest and agriculture are pronounced and therefore characterization factors should be differentiated. These results suggest that the integration of the ecosystem functions impacted by species loss complements existing approaches focusing on SR.

The resulting characterization factors' values were as expected for both FD and SR indicators: they were higher for managed land use types, such as "agriculture, mosaic"

Table 3 New reference LU types applied in the sensitivity analysis, in comparison to the previous ones, for six studies, including all three taxonomic groups

Taxonomic group	Study	Previous reference LU type	New reference LU type
Mammals	Husband (2009)	Forest (*data 2005*)	Forest (*data 2006*)
	Sullivan and Sullivan (2006)	Forest, primary	Shrubland
Plants	Mayfield et al. (2006)	Forest, primary (*forested riverbank*)	Forest, primary (*tree-fall gap in forested area*)
	Sanchez Merlos et al. (2005b)	Forest (*dry forest*)	Forest, secondary
Birds	Best et al. (1995)	Floodplain forest	Grassland (*Upland forest*)
	Mas et al. (2004)	Forest, primary (*Forest_Belen*)	Forest, primary (*Forest_Irlanda*)

and lower or negative for close-to-natural or natural land use type. However, both indicators did not behave equally: this is due to the nonlinear differences on the impact caused by biodiversity loss, especially for birds and plants. At least for birds, this behavior has also been observed in other studies, such as in Flynn et al. (2009). Even though, significant differences between CF_{FD} and CF_{SR} have been found for only a few land use types, FD indicators represent a closer mechanistic link between biodiversity loss and resulting impacts in ecosystem functioning and stability.

However, we did not find a significant difference between sub-land use categories within the same category, such as "forest, primary" and "forest, secondary." The same was observed on the analysis done by de Baan et al. (2013). The comparison of the values of the FD based CFs to those based on SR was a focal point of this study. It should however be noted that this only indicates whether or not the new approach would lead to different results compared with current LCIA practice, while not providing insights into which approach is more justifiable and representative. It can therefore not be the sole selection criteria between both approaches.

4.1 Classification of land use types

The first consideration in interpreting these results is the classification of land use types to specific categories in each study (see Table 1). This involves certain subjectivity on the associations made and relies on the description of land use types by the authors of the studies. In some of them, only few details were given on the specific land covers. The category "forest," for example, is used, when not enough information is obtained for more detailed classifications such as "forest, primary" and requires only that "an area should be covered more than 15 % by trees." Differences between "forest, primary"—"forests minimally disturbed by human impact, where flora and fauna species abundance are near pristine" (Koellner et al. 2013)—and "forest, secondary"—"areas originally covered with forest or woodlands, where vegetation has been removed, forest is re-growing and is no longer in use" (Koellner et al. 2013)—have not always been clear in the studies. For other forest types "forest" and "forest, extensive," few data points have been found within all data. The differentiation among them and other forest types relied on information gathered in the studies and was shown to be small.

4.2 Sample sizes

The second consideration for these results is the relatively small sample sizes for the number of communities in each land use type. Ecosystem processes result from the interactions among species and the higher the sample size, the better it is to define the difference between the simple presence or absence of a species versus the functional change in ecosystem characteristics (Chapin III et al. 2000). Small sample sizes might not be adequate to verify the variation, especially to what concerns SR × FD measures. The analysis of land use types has been conducted across different taxa and ecoregions and this could have influenced the results.

4.3 Functional traits

We used a single set of functional traits for the calculation of the FD values. Those traits have been considered by Flynn et al. (2009) and suggested to relate to resource capture which is the foundation of many ecosystem functions. This helps to predict the differences in results between loss of FD and SR.

However, in order to better evaluate the magnitude of change due to these functional characteristics, different data would be needed. For example, in mammals the trait of "offspring size for each species" could drastically change as SR declines. However, linking such changes in trait diversity to ecosystem functions is challenging, due to relatively few data available within given land use types and limitations of such trait data.

4.4 FD and SR indices

The results also show the importance of considering complementary information on species presence-absence and their functional role in the ecosystem. The quantification of aspects of species allows a better detection of specific community response to environmental change and impacts to ecosystem processes. However, a loss of species may also signalize a potential change in the ecosystem functional balance, if changes in FD and SR are similar.

5 Conclusions and recommendations

Currently, biodiversity indicators used are mainly based on taxonomic measures, such as SR. Furthermore, they do not take into account important factors such as species endemism, abundance or species vulnerability status, such as identified in the IUCN Red List (IUCN 2001) categories classification (Souza 2010). These might be crucial for the definition of species loss in a local, regional, or global scale and also on the capacity of a certain species to recover in a certain environment. Although, FD does not necessarily include data on these factors, it represents an improvement towards a more mechanistic linking between species loss and ecosystem processes and stability.

The use of FD characterization factors is justified as it further allows a more precise detection of community response to environmental change and impacts to ecosystem processes, although less sensitive to changes and more conservative than SR factors. Clearer results would most likely be obtained with a larger sample size of communities within each land use type. The provision of characterization factors for more detailed land use types in LCIA, such as forest types and agriculture types remains an issue as the level of detail in the definition of different land use categories for LCIA does not correspond to biodiversity data availability. Clearly, more data collection is needed, also in order to enable the provision of characterization factors for a longer list of different land use types. Once the issues with data gaps can be solved, FD characterization factors represent a viable and functional improvement to current practice.

Following the recommendations and conclusions of the UNEP-SETAC Life Cycle Initiative working group on LCIA of land use (sub-group of the working group on LCIA of natural resources and land use), the modeling of midpoint indicators such as Ecosystem Services Damage Potential and Biodiversity Damage Potential was not yet made operable. This is mainly due to the need to better understand the interactions among species and with their environment and to broaden the data compilation on different land use types. Therefore, although the current characterization factors are proposed at the midpoint level, it helps pointing out possible links between species loss and key ecosystem functions.

The integration of FD in the characterization factors for land use impact assessment is not an easy task. Species composition needs to be assessed for different land use type categories, and data on specific functional traits need to be compiled from the literature or directly measured. The final characterization factors also involve the calculation of a FD index and the existence of different metrics might bring differences in the results. The choice of the set of functional traits to be used in the calculations may also be a topic of concern. However, there is an ongoing effort in order to operationalize characterization factors for land use impacts on biodiversity and ecosystem services under the UNEP/SETAC Life Cycle Initiative. In line with the results found, we propose the use of SR indicators, alongside with FD indices in the assessment of ecosystem quality impacts, once they should not be combined in one index. This will also allow a better understanding of changes in ecosystem functions due to species loss. FD based characterization factors allow a clearer link between species loss and ecosystem quality indicators, allowing a better link between midpoint indicators (biodiversity loss) and endpoint indicators (loss of ecosystem functions).

Beyond biodiversity, land use impact indicators in current LCA are covering a growing range of impact pathways, such as biotic productivity, carbon sequestration, albedo, erosion regulation, or water capturing and filtering/cleaning for example. When discussing FD indicators for biodiversity, it is essential to clearly delimit these service functions partially provided by ecosystems from the functional traits covered by a biodiversity indicator in order to avoid double counting. The functional traits considered in this study are resource capture and overall life history strategy, which are both related to maintaining the ecosystem (and therefore biodiversity).

Ultimately aiming to increase the reliability (i.e., both accuracy and precision) and environmental relevance of land-use characterization factors by modeling relevant mechanistic relationships between land-use and biodiversity impacts this study explored the application of a FD based indicator as a complement to SR. Indeed, biodiversity can be assessed based on different measures (i.e., taxonomic and functional) and a possible recommendation would be the possibility to include multi-indicator, capturing many aspects of biodiversity and allow the assessment of a range of functions. However, this option is not only data demanding, but also requires a better understanding of species interactions in an ecosystem.

In LCA application, the FD characterization factors can be used in the exact same way as the current SR-based factors and do not require life cycle inventory data different from the latter. The more abundant data availability for plant-SR leads to a broad application of this indicator in current LCA practice, assuming good representativeness for overall biodiversity. Nevertheless, next to better representing ecosystem services and stability, another important advantage of the FD indicator is the inclusion of mammals and birds and hence a more complete representation of terrestrial ecosystems than just plants. However, this strength comes with a price as operationalization of this approach for global application in LCA is currently limited by the availability of input data representing the entire globe and all relevant land use types. We thus observe a trade-off between data availability/global coverage and representativeness/mechanistic linking to ecosystem functions when concluding on which indicator to prefer. Assuming that data availability can be increased with further research efforts, FD is a promising biodiversity indicator, which should not be neglected or abandoned in future research since this study observed several significant differences to SR.

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